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PRELIMINARY STUDY OF THE LUNAR ORBITER GROUND DATA PROCESSING SYSTEM

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PREPARED FOR:

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4. The unusual reflective characteristics of the moon's surface are an important consideration in determining the exposure requirements. For example, at 60° latitude for a full moon orbit, this so called "lunation" effect and the cosine effect combine to decrease the brightness to about one-tenth that at 0° latitude. No severe exposure problems are anticipated for the low resolution FCIC camera but further consideration must be given to the high resolution camera for which the exposure time is one-tenth and the lens aperture is f/10 compared to f/4 for the low resolution camera.

For the mapping requirements of the Lunar Orbiter System:

5. The photogrammetric accuracy is limited primarily by the navigational accuracy and the lack of absolute control points on the moon. Nevertheless, it should be possible to determine relative elevations within a few tens of meters. For ten-meter accuracy, the roll and pitch sensors should be accurate to 0.1 milliradian at an altitude of 100 km and the V/H sensors should have an accuracy better than 0.5%.

6. Storage of the data obtained from the lunar orbiter, although an extensive task, is not beyond the present day state of the art.

7. For certain times in the lunar month, transmission without interference from signals reflected from the moon's surface can be accomplished only about 81% of the time that line of sight prevails.

PART I

COMMENTS ON THE VOIS

Part of the effort carried out under the initial contract period was directed toward a brief study of the characteristics of the VOIS proposed by FCIC as they affect the ground data processing requirements. The following aspects were studied: sensor stabilization, photogrammetric requirements, fiber optics, magnetic tape recording, exposure and selection of the orbit. These are discussed in the following sections.

1.1 STABILIZATION REQUIREMENTS

Limits for rotation of the satellite have been established previously as $\pm 1°$ for roll and pitch, and $\pm 2°$ for yaw. The extra coverage needed to allow for such rotations does not place an important limit on system performance. It is also necessary, however, to determine limits for the roll, pitch, and yaw rates which may be allowed, since these directly affect resolution.

The amount of image motion (in the plane of the fibers) at the center of the fiber lines resulting from roll is given approximately by $d = f\dot{\theta}t \sin\alpha$, and that from pitch by

$$d = \frac{f\dot{\theta}t}{\sin\alpha}$$

The image motion resulting from yaw at the ends of the fiber lines is $d = h\dot{\theta}t$. Here d is the amount of motion, f is the focal length of the lens, t is the effective exposure time, h is the distance from the center of the "format" to the ends of the fiber lines, $\dot{\theta}$ is the rate of rotations, and α is the angle between the lensaxes and the plane of the fibers (see Figure 1). These equations neglect small variations over the camera field. For the 10-meter resolution cartographic camera, f is 12 inches (3.05×10^5 microns), t is 1/216 second, h is about 6 inches (1.5×10^5 microns), and $\alpha = 64°$.

The distance between fiber centers is 21 microns. An image motion of half that can be allowed without a significant loss of image resolution. Inserting these values into the above equations indicates the following allowable rates:

roll $\simeq$ 8 milliradians per second

pitch $\simeq$ 7 milliradians per second

yaw $\simeq$ 15 milliradians per second

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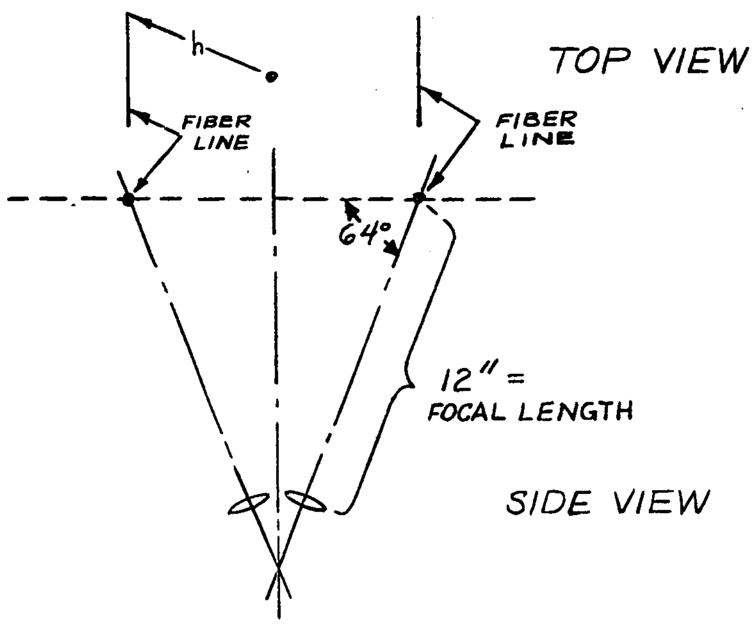

Figure 1 MULTIPLE LENS CARTOGRAPHIC CAMERA

For all the proposed FCIC cameras, the fiber size is the same and the focal length is inversely proportional to the effective exposure time. Thus the allowable roll and pitch rates will be the same for all three cameras. For the one meter resolution camera, the distance h is less (about 2-3/8 inches) and the effective exposure time is 1/10 that of the 10-meter resolution camera. Thus, the allowable yaw rate is about 20 times as high and will not affect the stability requirements.

The stability requirements indicated by the above calculations are not severe and should be readily met through proper design of the vehicle.

1.2 PHOTOGRAMMETRIC ACCURACY

The basic camera system, exclusive of the tape recorder, has no moving parts and is, therefore, capable of providing excellent photogrammetric accuracy by means of proper calibration. It is thus necessary to determine what equipment, both in the vehicle and on the ground, is necessary to make use of the full accuracy potential of the cartographic camera.

The resolution of 10 meters limits the ground location accuracy, both planimetric and vertical to the same order of magnitude. This 10-meter ground resolution element corresponds to an angular deviation of 0.1 milliradian, or a distance in the focal plane of about 30 microns.

The limits of measurement accuracy of a point in the image plane are given by the possible accuracy of camera calibration and by changes due to mechanical and thermal strain. The calibration accuracy should be equivalent to that obtained with ordinary mapping lenses which is about 5 microns. Mechanical strains should be small. With reasonable temperature control, thermal variations will also be small. For example, if the structural material between the lenses and the plane of the fibers were aluminum, which has a thermal expansion coefficient of about 10^{-5} per degree F, then a temperature variation of $\pm$ 20°F would be required to cause the lens-to-fiber distance to change sufficiently to produce a $\pm$ 10-meter ground error.

The orientation of the camera, however, will result in large errors unless carefully measured. To obtain the same relative error from this source as from the camera itself, the orientation must be measured and transmitted to the ground with an accuracy of 0.1 milliradian. This is a very strict requirement and it is not known whether the roll and pitch sensors will have the required accuracy. V/H sensors, which can be used to determine yaw angle, can be expected to have an accuracy of 0.1% to 1%. For a yaw angle of 2°, which is expected to be the maximum, the error in its measurement would be 0.05 milliradian for a V/H sensor error of 0.1%.

Errors in knowing the location of the satellite will result in similar errors in the horizontal or vertical location of objects on the moon's surface. However, even without a knowledge of the exact location of the satellite, relative elevations can be determined accurately over large regions using stereo triangulation. The satellite covers a distance of about 100 km between successive stereo scans of the ground at a speed of about 1500 meters per second. Thus for a 10-meter relative accuracy, the time between successive stereo scans should be measured to within a few milliseconds. This should not be a severe requirement.

Thus it is indicated that high accuracy may be attainable provided that adequate orientation sensors are employed and that the magnetic tape recorder or the data link does not substantially degrade resolution and destroy, or otherwise prevent the effective use of time signals or calibration marks.

The ground processing equipment must possess similar accuracy if the basic metric accuracy is to be preserved. This requires careful design and handling, but is well within the capabilities of standard photogrammetric methods, providing that a clean record is obtained from the VOIS-DSIF systems. Further photogrammetric considerations are discussed in Part III.

1.3 FIBER OPTICS

Illumination should present no serious problem since fibers having lengths of a few feet transmit a large portion of the incident flux, assuming proper numerical aperture.

With the 100 kilometer altitude and 120-inch focal length camera lens, a one-meter ground resolution requires an over-all "film" resolution of 17 lines per millimeter. Using disk point-spreads where the form is not specified, and using a resolution criterion of 4% contrast transmission, allowing for (1) empirical fiber transmission (Kapany)[1], (2) smears due to exposure, (3) mirror imperfections of one-eighth wavelength (Fairchild report), and (4) electron beam broadening of the order of magnitude of the fiber diameters (or alternatively, the readout system), the total resolution is 17 lines per millimeter. The calculation is approximate, particularly in that transfer function analysis is not well-suited to an exact description of the image recorded from a nonvibrating fiber bundle. It is considered that the combined effect of the above factors will degrade the imagery to levels somewhat below that calculated.

The construction of fiber bundles containing tens of thousands of fibers appears to be within the capability of present fiber optics fabrication. Similarly the production of fibers having diameters as small as 10 microns appears to be achievable within errors of a few per cent. Experimental work has been carried out on the use of a fiber bundle as itself the face of a cathode ray tube, with success.[1] Such instruments can probably be developed (if access to all experimental results is freely attainable) in less than a year -- possibly sooner. Some work has been done on the study of the proper phosphors, glasses, heat treatments, etc., required in such fabrication.[1] Nevertheless, this part of the fabrication would be experimental in nature, and results within a particular time limit may not be guaranteed.

1.4 MAGNETIC TAPE RECORDING

Since the limited bandwidth (1.0 megacycles per second) of the data link does not permit real time transmission of the high resolution video data from the vehicle to the earth, which requires a bandwidth of 4.3 megacycles per second, it is necessary to record all high resolution data, even when line of sight prevails, and transmit it at a slower rate. Thus, the tape recorder in the vehicle must be capable of recording with a bandwidth of at least 4 megacycles per second. This requires head-to-tape speeds exceeding 1000 inches per second. These high speeds are achieved presently by rotating the tape heads to produce a sequence of tracks as the tape is advanced. Rotation of the heads at high speeds permits the tape speed to be reduced to a reasonable value which is commonly 15 inches per second.

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[1] Kapany, N.S., Eyer, J.A., Keim, R.E., "Fiber Optics, Part II. Image Transfer on Static and Dynamic Scanning with Fiber Bundles", Journal of the Optical Society of America, Vol. 47, No. 5, May 1957, p. 423.

The high head-to-tape speeds required in video recording limit the lifetimes of the tape heads due to friction as the head crosses the tape and the wear that occurs as the head advances across the edge of the tape. Apparently the latter is particularly significant. Head lifetimes for conventional four-head systems are reported to be 400-500 hours.[2] The tape life is 100-300 passes. For a single head system developed at Foshiba Matsuda Research Laboratory in Japan, head lifetimes of 30-50 hours are reported.[3]

In typical video tape recording systems only one pair of side bands is generated and only the lower sideband is passed by tape readout. The resulting mixed AM-FM signal is limited, thus removing the AM and regenerating the upper sideband. The nonlinear nature of a system of this type might cause some difficulties in an application such as that proposed. In commercial TV the integration of successive frames by the eye eliminates some distortion and reduces noise.

The general problem areas for application to the Lunar Orbiter System would appear to be (1) the question of providing a 30-90 day recording lifetime in spite of tape head wear, and the associated problem of preserving satisfactory image metric qualities if tape-head replacement during orbiting is required, and (2) the question of the noise and distortion levels in a line-scan readout in contrast with the normal multiple frame TV applications.

1.5 EXPOSURE

A review has been made of the basic factors which influence the calculation of exposure requirements. From this, it has been concluded that several factors considered by FCIC would bear further examination to assure the feasibility of obtaining sufficient exposure with the high resolution (1 meter) camera. Three major factors are considered here: illumination and reflectance of the moon's surface, quantum efficiency of the detector, and contrast.

The exposure calculation has been made for full sun illumination, that is, for the satellite passing over the equator, with vertical solar illumination. Toward the poles, the illumination decreases as the cosine of the latitude. Furthermore, the surface of the moon has unusual reflective characteristics.[4] These depend on the phase angle, which is defined as the

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2 Journal of the Society of Motion Picture and Television Engineers, Vol. 69, No. 12, December 1960, p. 861.

3 Ibid, p. 868.

4 Van Diggeln, Johannes, Doctoral thesis at the University of Utrecht, Holland, June 1959, "Photometric Properties of Lunar Craters", Summarized by Struve, Otto, Sky and Telescope, pp. 70-74, August 1960, "Photometry of the Moon".

angle between the line of sight from the camera and the direction to the sun. The reflectance of the moon appears to decrease rapidly with increasing phase angle, so that at 30° the relative reflectance is about 50% of maximum; at 60°, about 20%; and at 90°, about 10%. This is an average over the entire moon's surface.

Combining the cosine effect and this "lunation" effect gives a decrease in brightness to about 10% at 60° latitude for a full moon orbit as planned.

The assumption of quantum efficiency for the calculation of detector signal/noise ratios assumes that the noise in the detector is primarily the photon noise. If a substantial amount of noise arises from the first amplifying stage, an exposure which is sufficient to eliminate photon noise may not be sufficient for the over-all detector. This is normally the situation which arises for vidicon tubes. The measure of "detective quantum efficiency"[5] has been suggested as the proper means to determine detector signal/noise ratios from the illumination levels. This has been measured for image orthicon tubes and has been found to be near the desired 10% level. Measurements on an ordinary vidicon indicated a value closer to 0.1%. Further study appears necessary to determine the characteristics of the return beam multiplier vidicon which has been recommended. Two matters are of interest. The first is whether the desired 10% detective quantum efficiency is obtained; the second is whether with such a tube the inherent advantages of the vidicon (size, weight, power, and reliability) are retained.

A final factor has to do with noise and contrast. The scene will consist of small variations about a large background brightness, the small variations comprising the signal of interest, and the contrast which can be detected depends upon the signal-to-noise ratio finally received. For example, for a contrast of 0.1, the useful (modulating) signal obtained will be only 0.1 of the total signal obtained for background brightness. Thus, if a signal-to-noise ratio of 50/1 is achieved for background brightness the useful signal-to-noise ratio for detecting low contrast information will be only 5/1. Since the expected contrasts are small, perhaps less than 0.1, this is an important effect.

In considering the 10-meter resolution cartographic camera, scan rates of 216 times per second for the vidicon were considered and indicated as feasible. Since no definite statements were made in regard to the required 2160 scans per second for the 1 meter resolution camera, further study of this problem is indicated. Of particular interest is the effect of the scan rate on the possible signal-to-noise ratio (as measured for example by the detective quantum efficiency).

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5 Jones, R. Clark, "Quantum Efficiency of Detectors", pp. 87-178 in Advances in Electronics and Electron Physics, Volume 12, Academic Press, New York, 1959.

1.6 ORBIT CONSIDERATIONS

The orbit which has been considered by FCIC provides maximum illumination with near vertical incidence at the equator of the moon. Since conventional photography of the moon (i.e., from the earth) commonly makes use of grazing illumination, the use of an orbit giving grazing illumination should also be considered. Thus, it is necessary to consider the choice of orbit in terms of the signal-to-noise ratio (and thus the contrast sensitivity), the resolution of the system, and the type of information which is to be obtained.

In general, as resolution improves, apparent contrast and surface roughness increase. Thus, illumination having a grazing angle of about 5° may not be necessary for the production of shadows. A low angle of illumination also provides a form of height magnification by producing a very long shadow. For the lunar orbiter, a long shadow will not be desirable. Resolution is such that a shadow the same size as the object will provide sufficient detail; furthermore, detail in the long shadow will be lost.

For the cartographic camera, the exposure is sufficient so that the signal-to-noise ratio will be limited by equipment other than the detector and amplifier. Thus, an estimate must be made of the expected signal-to-noise ratio, and a decision made as to whether the ratio is satisfactory to record the expected contrasts. If the expected contrasts will not be detected, then the use of shadows is necessary and the needed sun angle must be estimated. This is a substitution of the use of shadows for the low contrast resolution of the camera. With this procedure, the general decrease in illumination would be likely to result in the loss of all detail other than the shadow line.

PART II

PRELIMINARY REVIEW OF THE GROUND DATA PROCESSING SYSTEM FOR THE LUNAR ORBITER

The subsystem components required to provide the necessary information processing, display and storage for the Lunar Orbiter have been examined, and the basic factors to be considered for each of these subsystems for the establishment of system requirements have been outlined. In addition, a preliminary assessment of the over-all ground data processing system problem has been made.

There are a number of possible system concepts about which the ground data processing system requirements could evolve. Figure 2 is illustrative of a particular case. The basic subsystems relate to acquisition of the data, processing and conversion procedures, display, library storage and retrieval functions, and additional processing procedures for special requirements such as map preparation, image-enhancement, semiautomatic recognition capabilities, etc. In the outline material presented below, each of these functions is considered in more detail to indicate the relevant input-output factors to be considered in the specification of subsystem requirements.

2.1 PRELIMINARY ASSESSMENT OF THE GROUND DATA PROCESSING SYSTEM PROBLEMS

A review of the ground data processing system capabilities as considered to date, including the known preliminary characteristics of the input from the VOIS camera package, and the Laboratory's awareness of current state of the art equipments in the ground data processing field, indicate no areas for serious concern. It is clear, however, that the ground station requirements have a strong interdependence with the VOIS and DSIF subsystems; hence, early initiation of the ground data processing system design studies is recommended. Furthermore, there are a number of important problem areas which should receive special study consideration during the design phases. These include the following:

1. integration of the function of the observing staff in the ground processing requirements
2. formulation of a suitable library indexing scheme
3. definition of computer control and analysis functions
4. requirements for photogrammetric reduction of the VOIS data
5. review of the needs of the scientific community for Lunar Orbiter outputs
6. review of display projection geometries

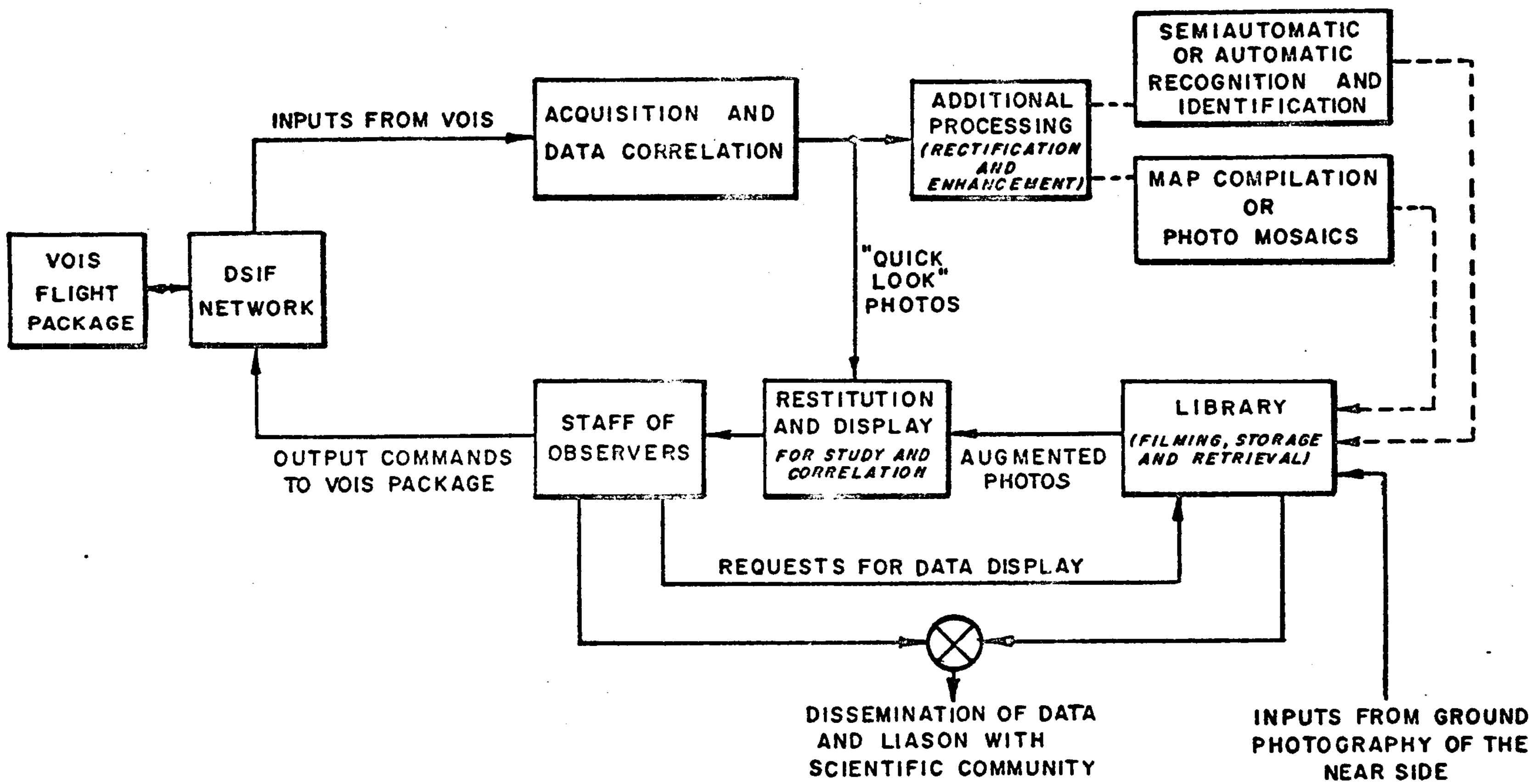

FIGURE 2 LUNAR GROUND DATA PROCESSING SYSTEM
(REPRESENTATIVE SYSTEM CONCEPT)

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7. consideration of special data displays for optimum use of high and low resolution recordings

8. review of feasibility for image recognition and image comparison techniques

2.2 PRELIMINARY OUTLINE OF OPERATIONAL CONCEPTS

The following is a preliminary outline of the operational concepts of the ground data processing system.

A. Subsystems

   I. Acquisition

   II. Conversion

   III. Displays

   IV. Library

   V. Additional Processing - Rectification and Enhancement

   VI. Computer - Analysis and Control

   VII. Auxiliary Functions - Mosaics, Maps, Charts, Recognition, Comparison

B. System Integration

   I. VOIS - DSIF - LUNADAP

   II. Lunar Orbiter (other sensors) - DSIF - LUNADAP

   III. LUNADAP - Surveyor, Prospector, Mariner

C. Subsystem Integration

   I. Acquisition - Conversion - Immediate Display - Observing Staff

   II. Acquisition - Control and Correlation - Rectification/ Mosaics, Maps, Charts

   III. Acquisition - Conversions - Library-Store/Retrieve

   IV. Observing Staff - Library Retrieval

2.3 PRELIMINARY ANALYSIS OF SUBSYSTEMS

A preliminary analysis of the various subsystems of the ground data processing system has been made in terms of those factors which affect the design requirements. The following is a preliminary list of these factors.

I. Acquisition

A. Inputs

1. Types

a. Low Resolution - Stereo

b. High Resolution

c. Additional Sensors

d. Auxiliary Data (Lunar Orbiter and DSIF) - chronometric, navigation, orientation, titling, synchronization, image motion, etc.

2. Formats

a. Electro-Optical/Photographic

b. Magnetic Tape

c. Thermoplastic Tape

3. Characteristics

a. Dynamic Range

b. Signal Level - Contrast

c. Bandwidth

d. Noise

e. Metric Qualities

4. Other Considerations

a. Rate of Input

b. Total Volume

c. Variations in Inputs

d. Reliability (Series/Parallel Flows, Redundant Design)

II. Conversion (Format)

A. Inputs (Types)

1. Electrical Scan Signal

2. Photo Negatives

B. Format

1. Frame

2. Continuous Scan

C. Requirements

1. Conversion; Continuous Scan to Frame

2. Conversion; Enlargement of Scan/Frame

3. Conversion; Reduction of Scan/Frame for Storage

4. Tape/Tape - Tape/Film

D. Input Considerations

1. Rate

2. Total Volume

3. No. of Different Outputs Required

4. Information (quality, metric)

E. Outputs

1. Tapes - Pictures/Charts/Alphanumerics

2. Negatives

3. Prints

III. Displays

A. Inputs

1. Low Resolution - Stereo and Mono
2. High Resolution - Mono
3. Other Sensors
4. Auxiliary Data
5. Maps/Charts
6. Photomosaics
7. Previous Coverage - Frames/Tapes

B. Input Considerations

1. Rate of Display
2. Correlation of Displays - (Positioning/Orientation)
   - Low and High Resolution Photos/Maps/Charts/Other Sensors
   - Comparative Coverage
3. Number of Displays
4. Type of Displays - Continuous Scan/Frame/Stereo/ Overlaps/Marginal Information

C. Requirements

1. Format - Size/Shape
2. Resolution
3. Brightness
4. Stereo/Mono
5. Projection/Viewer
6. Multiple Displays
7. Rapid Access/Changeover
8. Programming Capabilities

IV. Library

A. Inputs

1. Original Recordings/Copies - Low Resolution-Stereo
   - High Resolution
   - Other Sensor Outputs

2. Copy Masters

3. Framelets (Rapid Storage/Retrieval)

4. Enlargements - (Dissemination)

5. Rectified Prints/Enhanced Prints

6. Photomosaics

7. Maps (Small and Large Scale)

8. Charts

9. Overlays

10. Comparison Data - Ground Photography/Charts
    - Previous Lunar Orbiter Coverage

11. Recognition Files

B. Index Scheme

1. Orbital

2. Time

3. Derived Coordinates - Navigation
   - Earth Grid

4. Lunar Landmark (Low Resolution Systems)

5. Photogrammetric Network (Selenodetic Grid)

C. Sorting and Search Procedures

1. Sequential File/Search

2. Random File/Search

3. Category File/Search

4. Buffer Storage for Sort/Search

5. Handling Considerations

D. Storage Media/Format

1. Tapes/Frames

2. Microprints

3. Mosaic Prints

E. Input/Output Considerations

1. Observing Staff Requests

2. Scientific Community Requests

3. Input Rates, Dead Times

4. Total Volume

5. Correlation of Related Data

a. Auxiliary Data

b. Other Sensor(s)

c. Previous Coverage

d. Earth Photos/Nomenclatures

V. Additional Processing

A. Rectification

1. Inputs

a. Electrical - (Direct or from Magnetic Tape)

b. Uncorrected Photographs

c. Thermoplastic Tape - (Segmenting Probably Required)

2. Processing Procedures

a. For electronic signal processing

i. Cathode-ray tube display - vertical and horizontal deflections controlled by computer

ii. Image CRT trace onto film - to obtain required resolution segmenting required

b. For photographic image processing

i. Electro-optical scan of photographic transparencies (flying spot scanners)

ii. Optical scan

iii. Feed-in correction (computer inputs)

3. Input Considerations

a. Rectification of camera motions

b. Rectification of camera/ground-readout distortions

c. Correction of data link distortions

B. Enhancement

1. Inputs

a. Magnetic tape recordings

b. Unrectified tape/film recordings

2. Enhancement Methods

a. Selection of enhancement techniques (frequency and aperture filtering)

3. Functional Requirements

a. Reduction of random noise

b. Reduction of spurious noise

c. Enhancement of image qualities

i. Edge sharpening

ii. Contrast enhancement

d. Generalized spatial frequency and aperture-filtering for selected enhancement

VI. Computer

A. Inputs

1. V/H
2. Vehicle orientations
3. Time
4. Altitude
5. Orbit Data
6. Matching data for mapping

B. Outputs

1. Control signals to rectification units
2. Indexing and titling information to library storage
3. Mapping information (calculations for least square fitting, bridging, etc.)

VII. Auxiliary Functions

A. Mosaics

1. Uncontrolled (nominally corrected)
2. Controlled (photomap)

B. Maps and Charts

1. Small scale (total coverage)
2. Medium scale (areas of general interest)
3. Large scale (areas of specific interest)

C. Recognition and Comparison

1. Matching with photographs made from the earth
2. Matching with photographs made from previous orbits or by previous Lunar Orbiters
3. Automatic or semiautomatic recognition of specific features.

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PART III

INVESTIGATION OF THE LUNAR ORBITER REQUIREMENTS

This part of the report covers the ten-day period from 8 March 1961 to 17 March 1961 during which time the efforts were directed primarily toward planning the program and familiarizing the additional personnel with the over-all system and the areas of immediate concern. In addition a brief review was made of the mapping and charting requirements, the data storage and retrieval problem and the data link system, particularly with respect to its effect on mapping accuracy. Due to the time limitation there was no opportunity to pursue a detailed study of all the aspects of these problems. However, a number of pertinent areas were investigated and some of the more important considerations are discussed in the following sections.

3.1 DATA LINK

3.1.1 Image Degradation

Attenuation, noise and distortions are three major problem areas which could serve to degrade the quality of sensor images and hence affect the photogrammetric accuracy. Some of the factors which should be investigated in order to establish the magnitude of these degradations are listed below.

A. Attenuation (Fading)

1. Atmospheric absorption (including effects of rain, etc.)
2. Interference from reflections from surface of moon or earth, aircraft, meteor trails, etc.
3. Atmospheric refraction (loss of coherence in wavefront, angle of arrival variations)
4. Ionospheric effects during disturbances
5. Antenna aiming errors

B. Noise

1. Internal - receiver noise

2. External -

natural - thermal noise from surface of moon, surface of earth, earth's atmosphere

- solar and galactic noise, direct or reflected from surface of moon or earth

man-made - transmissions from other radio systems

- noise from vehicles, machinery, etc.

C. Distortion

1. Bandwidth limitations of equipment

2. Interference from reflections from surface of moon or earth, aircraft, etc.

3. Atmospheric refraction effects

4. Non-linearities in equipment

5. Doppler shifts

3.1.2 Reflection of Transmitted Signals from the Lunar Surface

A preliminary study was made of how the satellite data link transmission time would be affected by the interference of the directly transmitted signals with those reflected from the surface of the moon. This condition prevails during the fraction of the line of sight time when the lunar surface intercepts any part of the beam diverging from the vehicle's antenna. The situation is shown in Figure 3 for the case in which the earth-moon line lies in the plane of the vehicle's orbit. For a carrier frequency of 2300 megacycles per second and a dish diameter of four feet the total beam angle is approximately 6°. Assuming an altitude of 100 kilometers and that the antenna is always directed toward the earth during line of sight, the angle ϕ is 16°. Thus, for $\phi \leq 16°$, that is, for

$$\frac{16 + 16 + 180}{360} \simeq 59\%$$

of the orbit period, no serious degradation due to reflections from the lunar surface is expected. This figure compares with 60.5% for the line of sight condition.

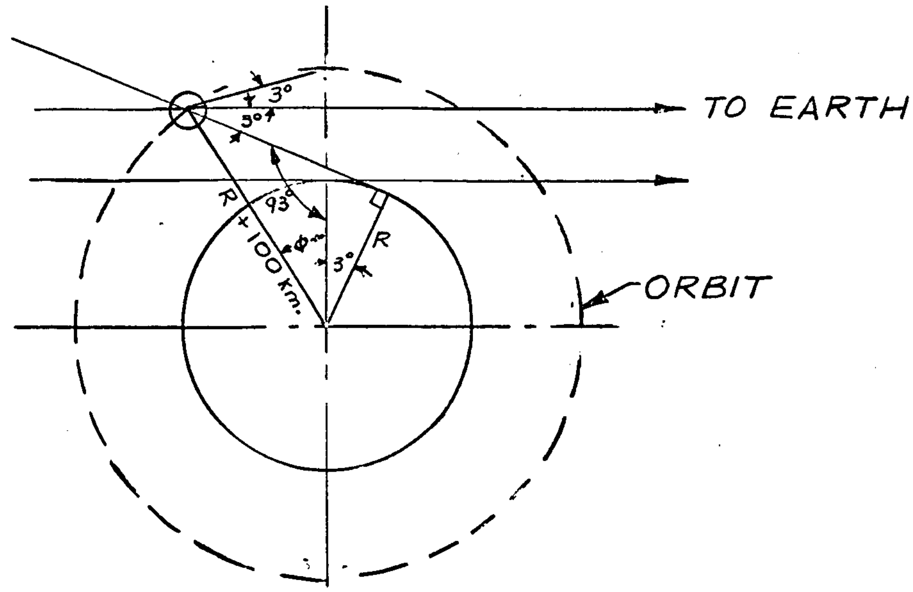

Figure 3 REFLECTION OF TRANSMITTED SIGNALS

In general, the earth-moon line will not lie in the plane of the vehicle's orbit and for a certain period of the lunar month line of sight will prevail during 100% of each orbital period. For the case when 100% line of sight first occurs, the fraction of the orbital period during which interference from reflected signals might be expected is about 19%. Thus, in this case transmission without reflection from the moon's surface can be achieved only 81% of the time that line of sight prevails. Then even though signals can be received throughout the entire two-hour orbital period, it must be realized that for more than twenty minutes of this period it is possible to have interference from lunar reflections. Since these reflections may degrade the image quality and limit the metric accuracy it seems desirable to use only that data obtained when reflections from the lunar surface are not possible.

3.2 AUXILIARY DATA FOR CHARTING PURPOSES

An initial effort was made to examine the primary areas relating to charting.

The package components for measuring auxiliary data should be determined by examining, first, the relative effects of each datum on the over-all map accuracy and, secondly, the various ways in which such quantities may be measured.

The basic concept underlying the use of an artificial satellite for charting is that of control extension. On Earth, for example, the orbital characteristics are determined from terrestrial stations which act as absolute geodetic control points. Orbit parameters then become a means of secondary control, and control extension is achieved by means of photogrammetric measurements (both of earth and sky, the latter providing orientation information). Ideally, therefore, the satellite is a means of easily and efficiently transferring geodetic control from known to unknown regions.

The basic concept of Lunar Orbiter charting is somewhat different, since there is no absolute Selenodetic control (in the same sense as the geodetic control previously discussed). The best substitute for such control involves measurements made from the earth, and could conceivably take two forms (or a combination of the two): (1) use of a Selenographic grid defined by astronomical data,[6] (2) use of earth based radar or optical systems to locate the Lunar Satellite with respect to the moon. Both techniques involve large probable location errors. To illustrate the errors that might be expected for the latter technique consider that for Earth satellites the best accuracy for position measurement was estimated[7] as about ± 100 meters for an altitude of about 1000 kilometers. Until absolute control on the moon's surface is attainable lunar mapping will remain less accurate than terrestrial mapping. The use of dynamic orbit data to obtain a lunar "geoid" or reference datum may be useful.

Finally, a few comments about the data processing system seem in order, inasmuch as its limitations affect the choice of package components.

It is evident that any cantilever extension technique will result in unfavorable propagation of systematic error, even though supported by auxiliary data (e.g., orbit parameters, and lunar "geoid"). However, the solution to this difficulty - general analytical stereotriangulation as developed by Brown,[8] Schmid,[9] and others - poses insurmountable practical problems, predominantly the required computer size, even in the case of a few hundred square kilometers of area. The area of the moon is roughly 38×10^6 square kilometers. It is unlikely that the completely general analytical techniques could be used, therefore.

Since absolute control is lacking, charts of the entire moon must be prepared in order to include the knowledge of the Lunar "geoid" and to adjust the systematic bridging errors. Within the state of the art it can be expected that even a very large data processing system will require a long

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6 Appendix, Army Lunar Construction and Mapping Program, House Report #1931, 86th Congress, 2nd Session.

7 Veis, G., "Geodetic Uses of Artificial Satellites", Smithsonian Contributions to Astrophysics, Vol. 3, No. 9.

8 Brown, D., "A Solution to the General Problem of Multiple Station Analytical Stereotriangulation", RCA Data Reduction Technical Report No. 43, February 10, 1958.

9 Schmid, H. H., "A General Analytical Solution to the Problem of Photogrammetry", BRL Report No. 1065, July 1959.

time to analyze the photography provided (order of years). Therefore, the auxiliary data that are taken should be capable of reducing systematic distortion of the photo-mosaic to a minimum, and should provide good relative-position information so that when absolute control points become available on the Lunar surface, the information may be profitably incorporated to strengthen the accuracy of the charts that have been prepared.

3.3 STORAGE OF DATA

The basic system input consists of lunar photography having a ground resolution of the order of 10 meters. Auxiliary data includes alpha-numeric information such as a location code (navigation data if unreduced data are stored) and previously compiled charts or photomosaics. Considering only the storage of the original or rectified lunar photography, an estimate of storage problems can be made.

Without advancing the state of the art of photographic-like systems, it is reasonable to expect to achieve resolvable spot sizes of less than 10 microns. Since ground resolution is about 10 meters, the scale for storage can be $1:10^6$. Assuming stereo coverage and low percentage redundancy, one complete lunar coverage can be stored on about 80 square meters of film. Since the original data are recorded by 5600 fibers per line or about 4000 resolution elements, the above criterion sets the format at 40 millimeters (which would probably be fitted to a standard 57-millimeter area of 70-millimeter film, allowing space for auxiliary data). Thus, the stated film area equals about 50,000 individual square frames.

A drum storage of individual frames might be used to provide an estimate of storage size requirements. Allowing 0.2 inch between frames for automatic retrieval equipment to grip any frame, 500 chips can be stored around the perimeter of a three-foot diameter drum. Since a single chip can contain both the fore and aft coverage of the same area, thus keeping stereo pairs together, only 25,000 chips need be stored, or 50 drum units. Allowing for mechanical rigidity, each drum unit would be about 4 inches high, so about 20 drums could be stacked as one unit, thus requiring less than 3 units to store stereo coverage of the entire lunar surface. Importantly, additional storage is necessary for previous coverage as well as for compiled maps, charts, photomosaics and other auxiliary data. A total of 7 units (3 feet diameter, 7 feet high, each) would be sufficient to store the expected input data, providing sufficient space for present state of the art equipment with automatic storage and retrieval. The assumed format would allow direct display by 10 power magnification, producing 10 lines per millimeter, approximately 2-foot square projections (optics would presently be a problem).

The description given above is necessarily only an approximation to the storage system which will eventually be used for the initial data. The storage need not be drums, it could be simply racks with a two-dimensional movement for the retrieval mechanism. The storage medium can be:

photographic with silver halide or other types of emulsions (such as diazo), electro-optic (Xerox, persistent internal polarization, thermoplastic recording, or electrostatic recording), or purely electrical (such as magnetic tape). The only assumption made in the above is that the data will be stored as separate chips to allow for random access. It is not likely that storage of data on long reels would afford fast enough access time, even if the reel were coded for automatic rapid search for each area.

The storage media mentioned above provide a variety of characteristics which must be considered in the choice of a storage medium. While an electrical input has the advantage that it allows direct write-in to storage from the data link, two difficulties arise. Magnetic tape, due to mechanical construction problems, requires about an order of magnitude more area than photographic-type systems for the same information storage. Systems which require an electron gun input presently achieve only 2000 resolution elements per line. In order to achieve the required 4000 elements, extremely sophisticated electron optics are required. Electrostatic tape requires electrical readout, causing similar difficulties. An optical input to storage can be provided by reversing the camera fiber system. Optical input and output, as in silver halide and diazo photography as well as Xerox and similar electrostatic latent image systems, remove the limit of a maximum number of resolvable elements per line.

Some systems, such as diazo emulsion photography, require too much exposure to be used to directly copy the real time input. However, diazo might be a valuable permanent storage, both due to its high resolution capability and its near transparency to IR. These features allow image micro reduction for small storage volume with high magnification display, since projector radiation does not appreciably heat the film.